

T-4  
Atomic & Optical Theory

## Superfluid Gas Mixtures

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Like condensed-matter superfluids, atomic-trap Bose-Einstein condensates (BECs) are coherent matter-wave systems. But as dilute atomic gases, BECs are amenable to the techniques of atomic physics and display a flexibility that is highly unusual for superfluids. A particularly exciting prospect—distinguishable boson condensate mixtures—is a subject of our research in T-4.

Such mixtures were created only recently in a laboratory environment: Ketterle's group at MIT and the Wieman-Cornell collaboration at JILA observed con-

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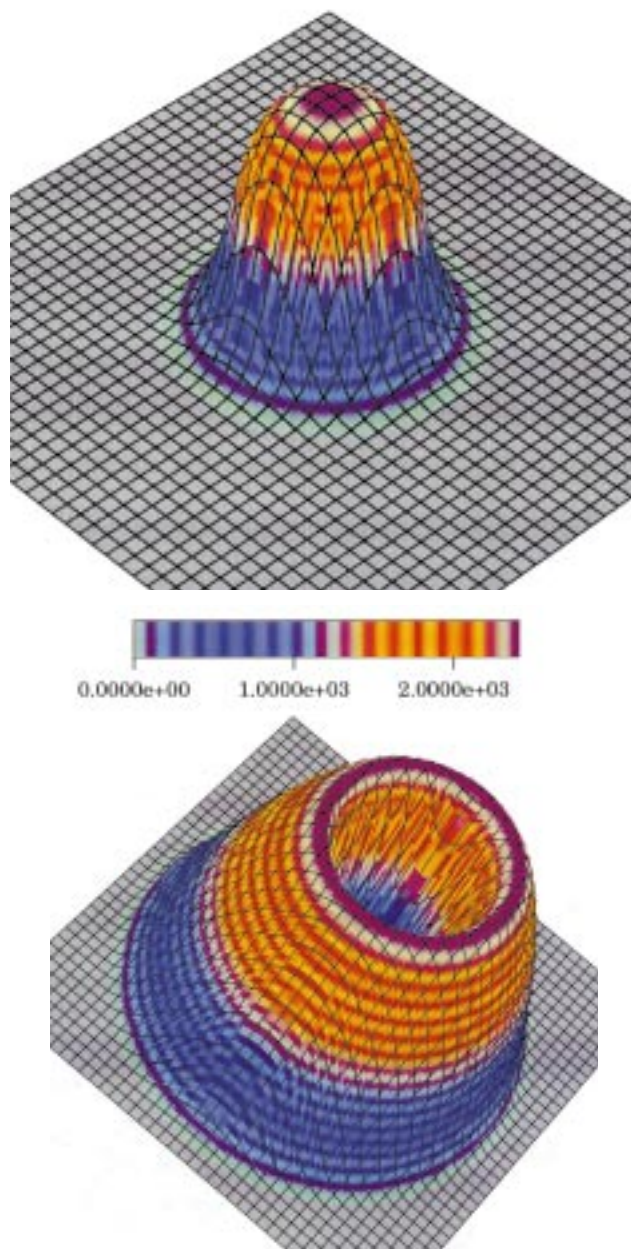
***Thus, the analysis suggests the BEC Feshbach resonance as a route to the creation of the first example of a rarified liquid.***

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densate mixtures of same-species alkali atoms in different atomic states. We pointed out that the condensates separate spatially into a system of immiscible fluids if the inter-condensate interaction dominates intra-condensate interactions. This prediction, which has since been verified in the MIT experiments, suggests interesting applications to BEC technology including the reintroduction of the concept of a 'wall' to confine one of the condensates.

Recent calculations, in collaboration with Lee A. Collins (T-4), have increased our understanding of the small condensate limit. For instance, we found that the immiscibility does not materialize unless the smaller one of the condensates contains a minimum number of atoms.

The condensates of a mixture can coherently exchange bosons. We have uncovered a rather surprising example of such inter-condensate tunneling: the BEC near the low energy Feshbach resonance originally proposed as



***Figure: Density distributions of two phase separated condensates in a spherically symmetric trap. The smaller condensate of  $10^5$  atoms (upper right) is surrounded by a larger condensate of  $10^6$  atoms (lower right).***

a scheme to alter the atom-atom interactions. The interactions that brings the atoms to an intermediate bound state molecule in the binary atom resonance create a second condensate component of molecules in the atomic condensate. The atomic and molecular condensates coherently exchange pairs of atoms. The system's time evolution can be characterized as coherent atom-molecule matter-wave dynamics. In response to a sudden change of the detuning, the populations of the atomic and molecular condensates oscillate in a Josephson-like manner. However, in contrast to Josephson exchange, two atomic bosons are required to form a single molecular boson. As a consequence of the resulting double condensate coherence, the many-body ground state has the liquid-like property of a self-determined density. The value of this density typically does not exceed present-day BEC-densities. Thus, the analysis suggests the BEC Feshbach resonance as a route to the creation of the first example of a rarified liquid.

Together with Peter Milonni (T-4), we studied the hybrid atomic/molecular condensates in an ongoing collaboration that involves physicists of different fields and different institutions: Arthur Kerman (MIT), Paolo Tommasini (Harvard), Robin Cote (Harvard, University of Connecticut) and Mahir Hussein (University of San Paulo, Brazil).

We plan to extend our studies to dilute fermionic superfluids, which are particularly relevant to anticipated experiments of David Vieira's group in CST-11 at Los Alamos.

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